EFFICIENT, MODULAR MICROWAVE PLASMA TORCH FOR THERMAL TREATMENT

Kamal Hadidi* and Paul Woskov
Plasma Science and Fusion Center
Massachusetts Institute of Technology
Cambridge, MA 02319 USA

ABSTRACT

A high-efficiency and high-power atmospheric pressure plasma torch has been operated in air and nitrogen by modularly combining two 2.54 GHz microwave plasma sources. Each modular plasma device uses a shorted waveguide within which the plasma is sustained. They are arranged in series so the second torch adds all its power to the output of the first torch to produce one high power flame. Total microwave power of 4 kW has been used in the present experiments by combining 2.5 and 1.5 kW sources. The microwave power coupling efficiency to the plasma has been determined to be approximately 95% by reflected power measurements in these initial unoptimized experiments. Plasma gas temperatures of approximately 5500 K have been obtained by spectroscopic measurements. A flame length of up to 25 cm beyond the second waveguide has been achieved for axial gas flows of up to 140 liters/minute through the 2.5 cm diameter discharge tube traversing the waveguides. The maximum power, number of modular stages, and gas flow volume is limited by the presently available hardware components. There is significant potential for scaling up. This novel approach can open new possibilities for thermal processing by using commercially available and low cost magnetrons at 2.45 GHz and 915 MHz. Capital costs could be less than a dollar per watt for high power systems (> 75 kW) and there would be no electrodes to wear out. These features could make this technology competitive with traditional plasma arc torches and RF induction plasmas.

INTRODUCTION:

The need for thermal processing in different areas of the industry such as municipal and solid waste destruction, radioactive waste vitrification, and clean material processing has triggered research and development of high power, contaminant-free, low-cost and low-maintenance plasma torches. DC and AC plasma arc technologies have been around for almost a century and are used in many thermal processes including waste remediation and materials manufacturing. One of the main limitations of this technology is the limited electrode lifetime, which consequently requires frequent replacement, increasing costs and maintenance [1].

Much research has been expended on improving the technology of plasma arc electrodes. Some plasma arc systems use water-cooled metallic electrodes. This solution increases the lifetime of the electrodes only to a few hundreds of hours, but at the same time introduces a safety concern because a water leak into the plasma can produce an

* Corresponding author: Hadidi@psfc.mit.edu

explosion. Other systems use graphite electrodes and can only operate in non-oxidizing environments otherwise they burn up [2]. The fact that DC and AC plasma arc technologies rely on electrodes to produce plasmas is also a big handicap for applications that require high purity for materials processing because of contamination with eroded electrode material.

To date there is only one established method for generating electrodeless plasma torches for thermal processing applications and that is the radio frequency (RF) induction coupled plasma. This thermal plasma technology is presently used in manufacturing processes where contamination can not be tolerated such as the semiconductor and fiber optics industries [3]. This technology has not been applied to waste remediation because it is not very efficient. The efficiency of coupling RF energy into the plasma is approximately 40% to 50% [4] and can drop significantly at high power (> 100 kW). The radiated RF power from the induction coil requires shielding for safety and prevents the possibility of combining RF torches to increase power.

Microwave induced plasma is another method for generating electrodeless torches, but until now, it has only been used at relatively low power. The main application has been in chemical analysis applications [5] and emissions monitoring [6]. Also there have been some experiments for destruction of halogenated organic compounds [7, 8]. Generally these systems have made use of resonant cavities to produce and sustain the plasma, which consequently limits the maximum power and efficiency.

As an example of an early microwave plasma device, J.D. Cobine et al. [9] describe a microwave plasma torch at power levels between 1 and 5 kW. This torch was operated in various gases and at different frequencies. This system used a resonant cavity and the microwave coupling efficiency to the plasma was not greater than 10 % when used with argon and 70 % for polyatomic gases. More recently, John E. Brandenburg [10] and John F. Kline described a large-volume microwave generated plasma using a commercial microwave oven at 2.45 GHz. This of course shows the possibility of using a readily available and commercially established technology for the production of atmospheric pressure microwave plasma. However, the system described was not a dense plasma torch.

Recently it has been shown that a resonant cavity is not necessary for sustaining a microwave plasma and that microwave to plasma coupling efficiency can be very high (>95%) [11]. The high power microwave plasma torch described here is an out growth of this earlier work. Without resonator structure to limit transmitted power density, very high power operation can be achieved. Also since all microwave power is either absorbed by the plasma or confined within a compact waveguide, there is no safety problem with radiated power. Combining microwave plasma torches to achieve higher power with multiple units is also possible since interference between adjacent torches is not significant. This paper presents initial experimental results of combining two such microwave torches to achieve one high-power efficient plasma flame.

EQUIPMENT

Figure 1 shows the layout and different components of the experiment. The plasma produced in these experiments used two 2.45 GHz microwave power sources of 2.5 and 1.5 kW from Astex Inc. The microwave radiation from each source travels inside fundamental mode WR284 rectangular copper waveguide, which is shorted at one end. The waveguide can be customized for a given application. A waveguide circulator at the output of each magnetron directs reflected power into a water-cooled dummy load to

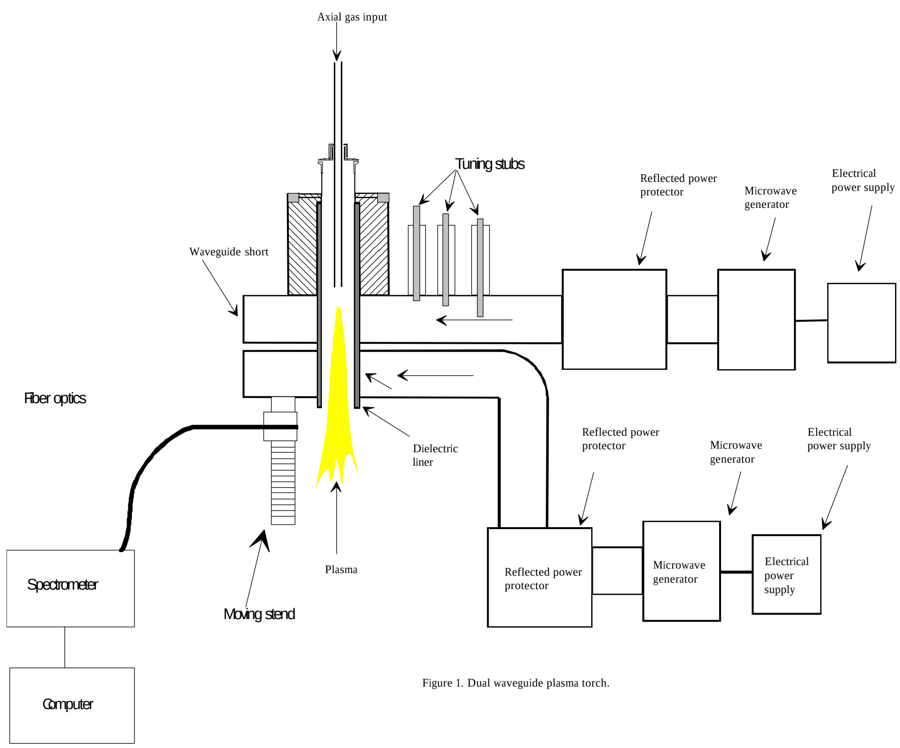

Figure 1. Experimental set up

protect the magnetrons from getting damaged during start up. A 32 mm diameter hole traverses each waveguide a quarter wavelength back from the short through which a 25.4 mm inner diameter boron nitride [BN] tube with 3.2 mm thick walls is inserted. It is used as the gas flow channel through the waveguides along the direction of the electric field. The plasma discharge is ignited by a 15 kV AC electric spark between two tungsten electrodes inside the plasma chamber just up stream from the first waveguide. The plasma is then sustained by the microwave radiation and maintained inside the boron nitride tube. It is kept from attaching to the walls by a swirl jet of air or nitrogen. Once the plasma is established, a triple stub tuner on each microwave source is used to match the plasma impedance to the microwave source to minimize the reflected power. A 6 mm inner diameter quartz tube, through which the axial flow is introduced, is inserted into the plasma chamber up to the base of the plasma. The axial flow rate can be varied from 14

liters/min [l/min] to 140 l/min. The swirl flow rate is varied from 4.5 l/min to 14 l/min accordingly with the axial flow rate to maintain stable and robust plasma.
Figure 2 shows a photograph of the microwave plasma torch for an air plasma at 112 l/min axial flow, 14 l/min swirl flow, and 4072 W total forward power. The reflected power with these parameters was 110 W at the first microwave source and 105 W at the second one. The overall coupling efficiency was therefore 95 %. The plasma presents a bright, homogeneous and stable flame. The length of the plasma outside the waveguide depends on the microwave power level and the axial flow rate. A graphite collar on the output of the waveguide as shown in the photo helps to minimize microwave leakage.

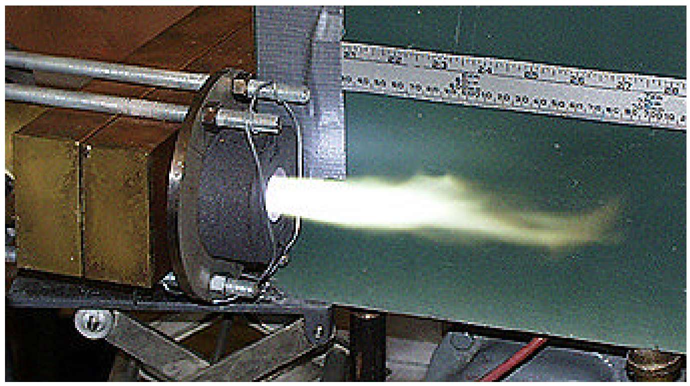

Figure 2. Microwave plasma torch in air

Detectors built into the Astex sources and calibrated by the manufacturer monitored forward and backward microwave power. During operation the reflected power is cross-coupled. The reflected power of one magnetron appears at the circulator of the other magnetron. This is probably the result of having the two waveguides too close together. There is less than a 2 mm gap between them in the present setup. Future reassembly with a somewhat larger gap between the waveguides should reduce this cross coupling effect. The total reflected power, however, is quite small, ~ 5%, relative to the forward power with the stub tuner properly adjusted.

A Simpson Model 380-2 Microwave Leakage Tester was used to monitor microwave leakage out of the waveguide and plasma chamber. At forward power levels up to approximately 2 kW, leakage was less than 0.5 mW/cm^2 within 2 cm of the waveguide and plasma structure, passing the OSHA regulation for kitchen microwave ovens in the home. At higher power levels and longer plasma flames leakage was detected along the plasma flame, requiring a distance of approximately a meter to comply with the OSHA limit. This leakage can be readily shielded and would not be an issue for a torch enclosed in a metal furnace shell.

A fiber optic cable and a grating spectrometer were used for atomic emission spectroscopy of the plasma flame. The fiber optic was terminated in a small 5 mm diameter lens with a view perpendicular to the plasma axis and mounted on a sliding stand to perform a scan along the plasma axis. The other end of the fiber optic was connected to a high-resolution grating spectrometer, which could distinguish molecular rotational transitions. This instrument used a 3600 groove/mm grating, a focal length of 0.84 m, and a 2,048 element StellarNet linear CCD array to detect a spectral region near 388 nm with a resolution of about 0.012 nm [12].

ANALYTIC BASIS FOR TEMPERATURE DETERMINATION

The gas temperatures were determined by measuring the rotational temperature of the N_2^+ ion in the plasma using the line-pair intensity ratio method [13]. It is assumed that the rotational temperature of the N_2^+ ion is equivalent to the gas temperature. This method takes the intensity ratio between two peaks, one from the R branch and the other from the P branch in one of the bands of the nitrogen ion molecule N_2^+. The emission intensity from an electronic transition of a diatomic molecule is given according to the following formula [14]:

$$I_{em} = \frac{C_{em}.\nu^4}{Qr} . [J'+J''+1]\exp[-B'J'[J'+1]hc/kT] \qquad \text{(Eq. 1)}$$

where I_{em} is the emission intensity of a given line, C_{em} is a constant depending on the change of dipole moment and the total number of molecules in the initial vibrational level, ν is the wavenumber of the emitted photon, J' the rotational quantum number of the upper level, J'' the lower level rotational quantum number, B' is the rotational constant of the upper state, and Q_r is the rotational partition function. By applying equation 1 to the R29 and P56 peaks of the 0-0 band of the $^2\Sigma$-$^2\Sigma$ N_2^+ transition and by taking the ratio of the two lines, The coefficient term outside the brackets cancels out and we obtain the rotational temperature through the following equation:

$$T_{rot}\,[K] = \frac{6421}{\ln\frac{I_{R29}}{I_{P56}} + 0.62415} \qquad \text{(Eq. 2)}$$

Similar relations can be derived for other pairs of transitions between different rotational levels.

Equation 2 can be a very accurate way to determine rotational temperature assuming thermal equilibrium of the molecular species. Because the emission frequencies of these two rotational transitions are almost identical the spectral response of the spectrometer is the same for each line. No wavelength dependent calibration of the spectrometer is required. Also because the rotational energy levels are far apart and the intensity ratio of the two transitions is nearly the same, the logarithmic intensity ratio term in the denominator is smaller than the other constant term. Small uncertainties in the measured intensity ratio do not contribute to a significant error in the temperature calculation.

RESULTS AND DISCUSSION

Figure 3 shows an illustrative spectrum for the microwave plasma torch of part of the 0-0 band of the $^2\Sigma$-$^2\Sigma$ transition of the nitrogen ion molecule N_2^+. The two peaks R29 and P56 used to calculate the rotational temperature are indicated on the spectrum. A temperature of 5000 K (5500 ± 500 K) was obtained for an all nitrogen discharge when viewing along the flame axis into the waveguide. This is in agreement with the results of K. Ogura et al. [15] who measured the rotational temperature in a microwave-induced nitrogen plasma using an Okamoto design. Another observation is that the N_2^+ rotational temperature stays approximately constant as the power increases. This is of course counter-intuitive at first. However, the plasma volume is observed to increase. Increasing microwave power does not make the plasma hotter, but increases its size. Also, when oxygen is added to pure nitrogen in the axial flow, the rotational temperature is observed to drop slightly as discussed previously [16].

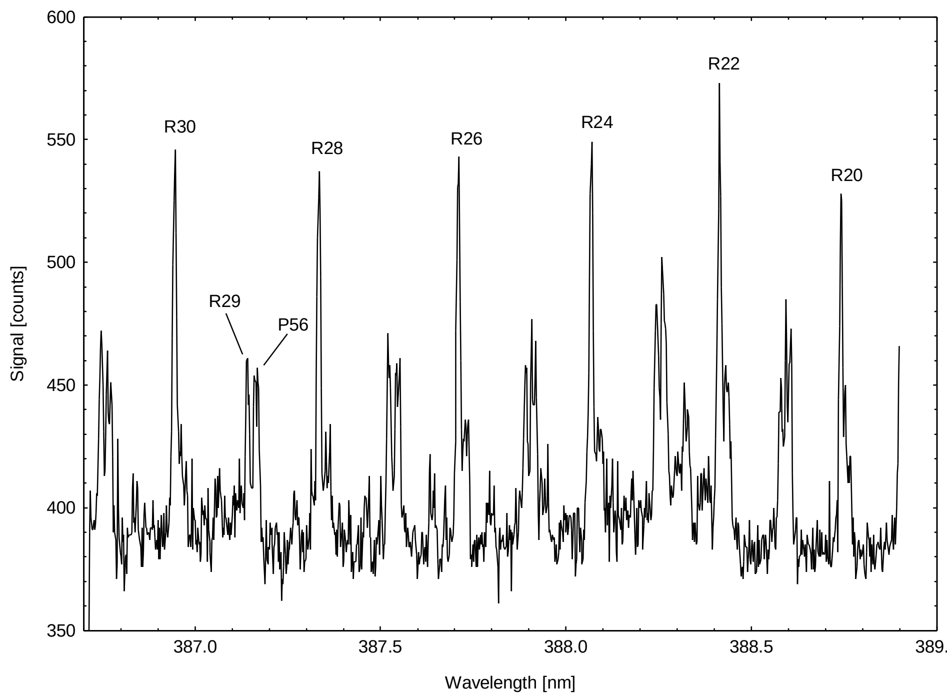

Figure 3. N_2^+ spectrum

A number of observations were carried out of the two-waveguide plasma torch to characterize its performance. These observations included output torch temperature as a function of gas flow volume, temperature along the flame axis, flame length as a function of gas flow, and ability to melt glass.

Measurement of the plasma temperature as a function of gas flow volume was investigated first at 10 l/min swirl flow, and 3.7 kW power level. As the plasma becomes longer due higher velocity gas flow, its core also extends outside the waveguide and the gas temperature measured right outside the graphite collar increases as shown in Figure 4. This temperature approaches the temperature of the plasma measured inside the waveguide as the axial flow rate increases. The temperature increased from 4200 K to about 5000 K as the flow increased from 30 l/min to 140 l/min.

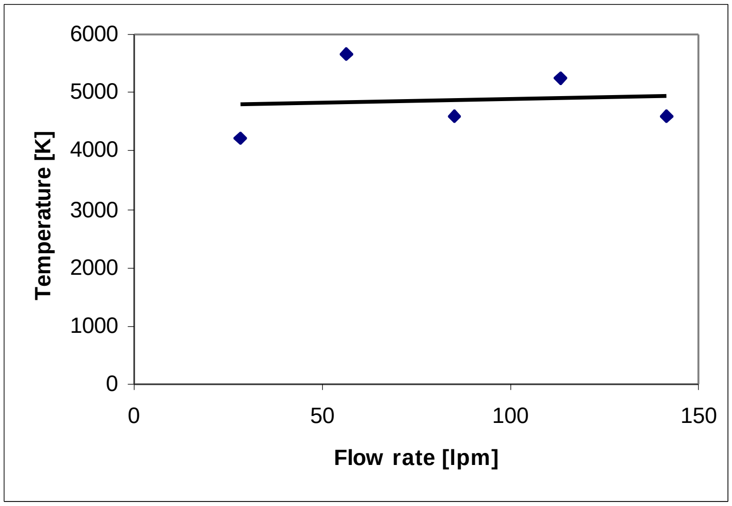

Figure 4. Plasma temperature measured at the waveguide

The corresponding plasma flame length was also measured as the axial flow rate was increased. The length was measured visually by placing a scale behind the flame. Measurements were taken from the base of the waveguide to the end of the plasma after-glow. The results are plotted in Figure 5. The plasma becomes longer when the axial flow rate increases. This is because, it is first created and sustained inside the waveguide, and as the axial flow rate increases, it is blown out farther. The axial flow rate can not be increased indefinitely otherwise the plasma is extinguished.

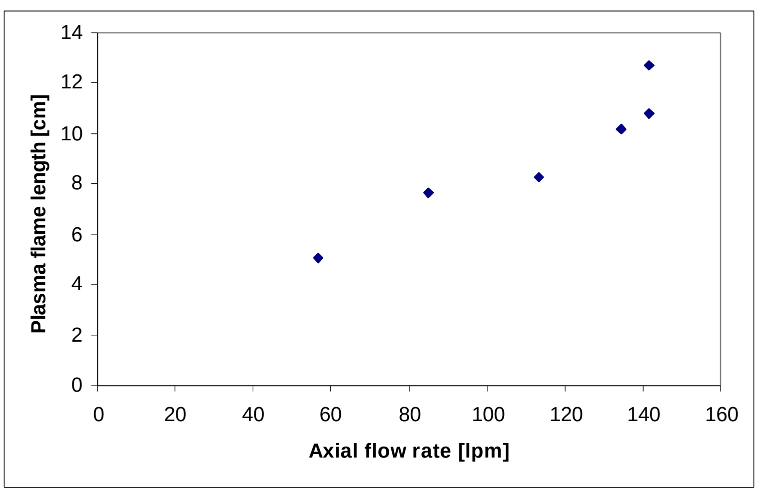

Figure 5. Plasma flame length versus axial flow rate

We also measured the temperature of the plasma after-glow by scanning the plasma outside the waveguide along its axis. Figure 6 gives this temperature of one of the N_2^+ rotational transitions versus the distance from the waveguide at an axial flow of 99 l/min and absorbed power of 3.9 kW. Also, the light intensity drops very rapidly as the number density of the excited N_2^+ species decreases. This can be attributed to rapidly decreasing electron densities and energies for creating and exciting N_2^+ outside the waveguide plasma region. However, the gas temperature by comparison drops very little from 5200 K at the waveguide to 4800 K 6 cm farther. Beyond this distance, the signal from the R and P branches of the N_2^+ ion is lost in the background noise, and the temperature cannot be calculated. The loss of emission light for temperature measurements doesn't signify a significant cooling of the gas or loss of enthalpy for thermal processing applications.

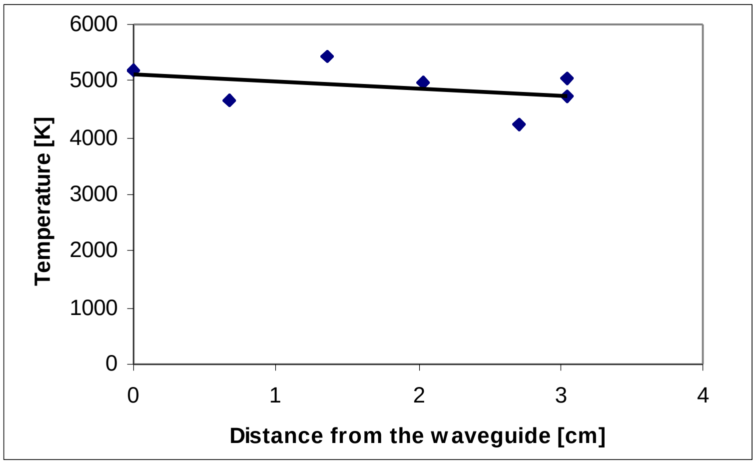

Figure 6. Plasma after-glow temperature in nitrogen

To test the capability of this plasma for thermal processing applications, a sample of bottle glass with a relatively high temperature for becoming fluid (~ 1400 °C) was melted. The an air plasma flame was directed towards the bottle, which started to melt and drip after approximately 15 seconds with the torch running at 3.9 kW. The glass was located about 3 cm from the graphite collar. This experiment demonstrates that the microwave plasma torch can be effective for thermal processes such as the vitrification of wastes.

Scale up of the present hardware to higher power levels would be needed to make a practical torch for economical thermal processing. This can be accomplished by one of two approaches. In the first, the hardware would be kept at the present frequency of 2.45 GHz. The single source torch power could be scaled up modestly to about 10 kW using higher power commercially available microwave magnetrons. Water-cooling could be added to the waveguide structure to handle the higher heat loads. Multiple sources could then be put together in a modular way as shown here to achieve torch power levels of several tens of kilowatts.

In the second approach, the source frequency would be decreased to 0.915 GHz where higher power and more efficient commercial sources are available. Reducing the frequency would also increase the waveguide cross-sectional dimensions by about a factor of three. The increase in dimensions would allow the power to be increased by a factor ten to get to the same power densities of the present experiments. Therefore, a single source microwave torch in the 50 –100 kW power range could be possible. Several of these could be combined to make torches with several hundreds of kilowatt power levels. Microwave sources at 0.915 GHz are widely used in the food processing industry and turn key systems can be purchased for less than one dollar per watt including the power supply [17].

CONCLUSION

A completely new approach for the production of efficient, high-power electrodeless plasma torches has been shown. Essentially there are two new developments described here. First, an efficient and robust microwave sustained plasma torch can be generated using a single microwave source in a shorted non-resonator waveguide. Second, such torches can be combined in a modular building bock fashion to achieve much higher output plasma power. Using two modular microwave sources with a total power of 4 kW, the temperature of a nitrogen plasma flame outside the waveguide has been measured to be between 4500 and 5500 K. It has also been shown that this plasma flame when operated in air has sufficient enthalpy to melt glass. There is significant potential for scaling up the present experiments to higher powers, possibly as high as several hundred kilowatts. It is apparent from this work that an efficient, robust and reliable microwave plasma torch can be developed for thermal processing in various environmental and industrial applications. The capital cost of such a torch could be in the vicinity of a dollar per watt. This could make it very competitive with traditional thermal plasmas such as arc plasma torches and RF induction plasmas.

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